PERFORMANCE EVALUATION OF REGULAR AND FIN-INTEGRATED OFFSHORE PIPELINES SUBJECTED TO TRANSVERSE PIPE DISPLACEMENT IN SOFT CLAYEY SEABED

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MARCH 2025

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by

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DEPARTMENT OF CIVIL ENGINEERING

submitted

in fulfilment of requirements for the degree of

DOCTOR OF PHILOSOPHY

INDIAN INSTITUTE OF TECHNOLOGY DELHI

MARCH 2025

Dedicated to my parents Ms. **Tanushree** and Mr. **Debashis Seth**,

and brother **Debopam**

DECLARATION

I hereby declare that, except where specific reference is made to the work of others, the contents of this thesis are my original work and have not been submitted, in whole or in part, for consideration toward any other degree or diploma at this or any other university. I further confirm that this dissertation is entirely the result of my own efforts and does not include any outcomes of work conducted in collaboration, unless explicitly stated. I also affirm that the guidelines provided by the institute have been strictly adhered to in the preparation of this thesis.

Date:

Debtanu Seth

New Delhi

CERTIFICATE

This is to certify that the thesis titled "**Performance Evaluation of Regular and Fin-Integrated Offshore Pipelines Subjected to Transverse Pipe Displacement in Soft Clayey Seabed**", submitted by **Mr. Debtanu Seth** to the Indian Institute of Technology Delhi is a record of bonafide research work carried out by him under our supervision and guidance. This thesis work, in our opinion, has reached the standard of fulfilling the requirements for a **Doctor of Philosophy** degree. The research report and results presented in this thesis have not been submitted, in part or full, to any University or Institute for the award of the degree or diploma.

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ACKNOWLEDGEMENTS

This research work would not have been possible without the invaluable support of numerous individuals, to whom I extend my heartfelt gratitude. First and foremost, I express my profound appreciation to my advisors, Prof. Bappaditya Manna and Prof. J. T. Shahu, whose exceptional guidance and unwavering support have been instrumental throughout my doctoral journey. Their profound insights, expertise, and dedication in reviewing countless drafts and providing constructive feedback have significantly shaped this thesis. The privilege of working under their mentorship has been truly transformative.

I am deeply indebted to the Student Research Committee (SRC) members, Prof. A.K. Keshari, Prof. P. Vangla, and Prof. B.P. Patel, whose insightful critiques and valuable suggestions have substantially enhanced the quality of my research. I extend my sincere appreciation to Prof. Tiago Ferradosa from the University of Porto for his collaborative spirit and significant contributions to our research endeavors.

I am particularly grateful to Prof. Vasant Matsagar, Head of the Department, whose leadership has been crucial in providing the resources and opportunities that have facilitated this research. I also acknowledge the constant encouragement received from the faculty members of the Department of Civil Engineering throughout my research tenure.

The technical support provided by the laboratory staff of the Geotechnical and Rock Engineering section has been essential to the success of this project. I extend special thanks to Mr. Dharmendra and Mr. Alok Kumar for their expert assistance during various stages of the experimental work. My sincere appreciation also goes to Mr. Manoj Kumar Nilam, Mr. Jiwesh Ram, Mr. Manish, and Mr. Ram Janam for their dedicated support during the model tests.

I am deeply grateful to my fellow researchers Ms. Namrata Bhattacharjee, Mr. Souryadeep Biswas, Mr. Koushik Das, and Ms. Sayanti Banerjee, whose camaraderie and intellectual support have enriched my research experience. Special appreciation goes to my seniors, Dr. Prasun Halder and Dr. Sujata Fulambarkar, for their mentorship, timely guidance, and constant encouragement throughout this journey. I extend my heartfelt gratitude to Ms. Baibhabshri Roy, whose steadfast support have been a source of strength along this endeavour.

I extend my sincere appreciation to my seniors who have been instrumental in this journey: Mr. Vinay Kr. Singh, Dr. Mayuresh Bakare, Dr. Deepesh Bansal, Dr. Harshal Peshne, Dr. Debiprasad Nayak, Dr. Debaprakash Parida, Dr. Abdullah Ansari, Dr. Kavita Tandon, Ms. Shipra Sinha, and Dr. Abhishek Srivastava. Their guidance and support have been invaluable. I am particularly thankful to my co-research scholars and friends who have shared this academic journey with me: Ms. Nekita Borah, Mr. Arpan Nandi, Dr. Ravi Raj, Ms. Sriparna Roy, Mr. Rajeev Ranjan, Dr. Somya Ranjan Patra, Mr. Ashwinth Raj, Ms. Stuti Mishra, Mr. Lalit Kandpal, Mr. Girish Chand, Ms. Shruti Raut, Ms. Gouri Nayek, Ms. Arpita Mondal, Ms. Jyoti Rani Nath, Dr. Akash Santra, Dr. Rita Majumdar, Dr. Arkajyoti De, Dr. Rupayan Roy, Mr. Subhashis Bag, and Ms. Adrika Banerjee.

I am deeply grateful to those who encouraged me to embark on this doctoral journey: Ms. Rituparna Das, Ms. Niharika Nahak, Dr. Sumit Kumar, Mr. Gaurav Anand, Dr. Mrinal Bhowmik, Ms. Sonali Raut, Ms. Manaswini Mishra, Mr. K.V. Balaya, Ms. Chitra Verma, Mr. Koushik, and Ms. Subhashree Dalai. I extend my heartfelt gratitude to Mr. Subhadeep Hui, Mr. Koushik Mondal, Mr. Ayan Guchhait, and Mr. Bivash Mondal for their steadfast friendship and unwavering support throughout this journey. Your encouragement and friendship have been invaluable, and I am deeply thankful for your presence during this significant chapter of my life.

I am profoundly grateful to my family, who have been the bedrock of my academic journey. My deepest gratitude goes to my parents, Ms. Tanushree Dey Seth and Mr. Debashis Seth, whose unwavering support and sacrifices have made this achievement possible. I am forever indebted to my grandparents, Mr. Jitendra Nath Dey, Ms. Shefali Dey, Late Mr. Samaresh Seth, and Ms. Uma Rani Seth, for their boundless love and blessings. Their collective patience, understanding, and steadfast emotional support have been my source of strength throughout this challenging journey. Without their unconditional love and encouragement, this accomplishment would have remained but a distant dream.

Completing this Ph.D. has been a challenging yet deeply fulfilling journey, and I am truly grateful for the unwavering support of so many wonderful people. Thank you for being part of this milestone and for making this experience so special. If I have unintentionally left anyone out, please know it is a limitation of memory and not of my gratitude. I also thank the Almighty for the health and strength that have carried me through. Lastly, I want to thank myself for believing, persevering, and embracing every step of this incredible journey.

Place: New Delhi

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ABSTRACT

Buried offshore pipelines are crucial for the swift transportation of oils and similar fluidised materials from the oil rigs to the processing centre or vice versa. However, offshore pipelines are susceptible to buckling due to their high slenderness ratio, and the resistance to such displacement relies on pipeline stiffness and soil resistance. A novel alternative of integrating radial fins into these pipelines was explored through a series of 1g laboratory model tests and numerical methods to mitigate the global buckling of pipelines by enhancing the global buckling resistance. Thus, in this study, the pipe soil interaction during the global buckling of a fin-integrated pipe section (FP) has been explored and compared with the buckling behaviour of a regular pipeline to understand the feasibility of the FP in improving the buckling behaviour of a pipe section. To fulfil this primary objective, a series of scaled model tests have been performed, followed by several finite element analyses, by varying the number and orientation of radial fins, pipe embedment depth, strength parameters of soil, and the direction of buckling-induced pipe movement. In the current study, the pipe-soil interaction of the offshore pipelines was considered for surface-laid pipelines subjected to vertical penetration and buried pipe sections subjected to vertically upward and lateral displacement due to thermal buckling. Furthermore, the load-displacement behaviour of the pipe, pressure around the pipe section, soil surface heaving, and the displacement field within the surrounding soil were examined thoroughly and illustrated and discussed comprehensively. The observation from the experimental studies and the prediction from the numerical studies helped to understand the buckling behaviour of offshore pipelines, along with the efficiency of the radial fins in enhancing the buckling resistance of the pipe sections. Moreover, a sensitivity analysis revealed the impact of various soil and geometric parameters on the buckling resistance and their order of influence. Finally, a general optimized pipe section was proposed to resist

buckling in each direction by balancing the material consumption and the buckling resistance provided by the particular fin configuration.

सार

दफ़न की गई अपतटीय पाइपलाइनों का तेल एवं अन्य तरल पदार्थों को तेल रिग से प्रसंस्करण केंद्र या इसके विपरीत परिवहन करने में अत्यधिक महत्व है। तथापि, अपतटीय पाइपलाइनों में उनके उच्च पतलेपन अनुपात के कारण बकलिंग (मोड़ने) की प्रवृत्ति होती है, और इस प्रकार के विस्थापन का प्रतिरोध पाइपलाइन की कठोरता और मिट्टी के प्रतिरोध पर निर्भर करता है। इस समस्या के समाधान हेतु, इन पाइपलाइनों में रेडियल फिन्स को एकीकृत करने का एक नवीन विकल्प प्रस्तावित किया गया है। इस अध्ययन में 1g प्रयोगशाला मॉडल परीक्षणों और संख्यात्मक विधियों की एक श्रृंखला के माध्यम से पाइपलाइनों की वैश्विक बकलिंग को कम करने और उनकी बकलिंग प्रतिरोध क्षमता को बढ़ाने का प्रयास किया गया।

इस शोध में फिन-समाहित पाइप खंड (FP) के वैश्विक बकलिंग के दौरान पाइप-मिट्टी परस्पर क्रिया का विश्लेषण किया गया और इसे परंपरागत पाइपलाइन के बकलिंग व्यवहार से तुलना की गई, जिससे पाइप खंड के बकलिंग व्यवहार में सुधार के लिए FP की व्यवहार्यता को समझा जा सके। इस उद्देश्य की पूर्ति हेतु, विभिन्न स्केल्ड मॉडल परीक्षण किए गए, जिनका अनुसरण संख्यात्मक तत्वीय विश्लेषण द्वारा किया गया। इन विश्लेषणों में रेडियल फिन्स की संख्या और अभिविन्यास, पाइप की गहराई, मिट्टी के शक्ति मापदंड, और बकलिंग-प्रेरित पाइप विस्थापन की दिशा में परिवर्तन किया गया।

अध्ययन में सतह पर स्थित पाइपलाइनों के ऊर्ध्वाधर प्रवेशन तथा थर्मल बकलिंग के कारण ऊर्ध्वाधर ऊपर और पार्श्व विस्थापन के अधीन दफ़न पाइप खंडों की पाइप-मिट्टी परस्पर क्रिया पर विचार किया गया। इसके अतिरिक्त, पाइप के भार-विस्थापन व्यवहार, पाइप खंड के चारों ओर का दबाव, मिट्टी की सतह पर होने वाले उभार, तथा आसपास की मिट्टी में विस्थापन क्षेत्र का विश्लेषण किया गया। इन अवलोकनों को गहनता से चित्रित और चर्चा की गई।

प्रयोगात्मक और संख्यात्मक अध्ययनों से प्राप्त निष्कर्षों ने अपतटीय पाइपलाइनों के बकलिंग व्यवहार को समझने तथा पाइप खंडों की बकलिंग प्रतिरोध क्षमता को बढ़ाने में रेडियल फिन्स की प्रभावशीलता को प्रमाणित किया। इसके अतिरिक्त, संवेदनशीलता विश्लेषण ने बकलिंग प्रतिरोध पर विभिन्न मिट्टी एवं ज्यामितीय मापदंडों के प्रभाव और उनके अनुक्रम को रेखांकित किया। अंततः, सामग्री खपत और विशिष्ट फिन विन्यास द्वारा प्रदान किए गए बकलिंग प्रतिरोध के बीच संतुलन स्थापित करते हुए प्रत्येक दिशा में बकलिंग का प्रतिरोध करने हेतु एक सामान्यीकृत अनुकूलित पाइप खंड प्रस्तावित किया गया।

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF SYMBOLS

a_1 , $a2, a3, a4$	Fitting coefficients.
A	Cross-sectional area of pipeline.
A_1	Calculation parameters relative to soil properties and experimentally determinate.
A_2	Modification coefficient of the normal stress on the pipeline and experimentally determinate.
A_s	Cross-sectional area of soil lifted in vertical slip mechanism.
A_{soil}	Area of soil block above the pipe.
b_1 , b_2, b_3, b_4 , b_5	Fitting coefficients.
B	Base width of the pipeline.
c_1	1.48
c_2	0.955
c	Cohesion of soil.
C_c	Compression index
C_s	swelling index
c_u	Undrained cohesion.
c_v	Coefficient of consolidation.
C_{22}	Element of stiffness matrix.
d	Maximum drainage path length during consolidation.
d_d	Depth of dent.
D	Pipe Diameter.
D_0 = (D-t)	Pipe mean diameter.
D_e	Elasticity matrix.
E'	Strain hardening modulus.
EI	Bending stiffness.
E_p	Modulus of elasticity of pipeline.
E_s	Modulus of elasticity of soil.
f	Yield function.

f_o	The initial ovality of the pipeline.
f_l	Lateral resistance of soil.
$f_{c'}$	Factor for the effect of cohesion on anchor behaviour and is a function of embedment ratio, friction angle and surcharge pressure above the soil.
f_{NBA}	Factor for obtaining $s_{u,eff}$ for the 'kz' component of s_u .
$f_{g'}$	The anchor capacity factor for the basic case of a smooth anchor resting in a soil and is corrected for soil dilatancy, anchor roughness and initial stress state.
F_{brk}	Breakout resistance of pipeline
ΔF_H	Horizontal loading rate
F_H	Horizontal loading on pipeline
F_R	Passive soil resistance exerted on the
F_Z	Vertical hydrodynamic lift load on pipeline
g	Gravitational acceleration
g_p	Plastic potential function.
h	Hardening modulus.
H_m	Maximum buckle amplitude of pipeline.
w	Buckle amplitude of pipeline.
I_p	Second moment of area of cross section of pipeline.
k	Incremental soil strength rate.
k_{cr}	Critical curvature of an initially dented pipeline.
k_i	Critical curvature of an intact pipeline.
k_{ou} and k_{ov}	Factors determining the initial stiffness.
k_u	Limiting value for the axial resistance.
k_v	Limiting value for the lateral resistance.
k_t	Rate of strength increase per decade
K	Coefficient of lateral earth pressure;
L	Buckle length.
L_0	Buckle length of the imperfection topology.
L_{cr}	Critical length of pipeline (Zhu et al. 2015).

M_{cr}	Ultimate bending moment of an initially dented pipeline.
M_i	Ultimate bending moment of an intact pipeline.
N_c	Capacity factor, a function of pipe roughness = 10
N_{ch}	Lateral interaction factor dependent on burial depth ratio.
N_p	Bearing capacity factor of the pipeline and function of the pipeline roughness ($9.14 < N_p < 11.94$) (Bransby et al. 2002)
N_u	Uplift capacity factor.
N_h	Horizontal capacity factor.
$N_{u(weightless)}$	Uplift capacity factor of soil considering weightless soil.
N_{u0}	Uplift capacity for pipe placed at the surface of weightless soil.
$N_{u(limit)}$	Limiting values of $N_{u(weightless)}$ as proposed by Randolph and Houlsby (1984).
p_h	Hydrostatic pressure.
p_i	Internal pressure on the pipeline.
P	Axial compressive force.
P_c	Collapse pressure for a pipeline.
P_{cr}	Critical axial force.
P_o	Yield pressure of the pipeline.
P_p	Buckle propagation pressure.
$P_{suction}$	Additional suction force per unit length.
P_v	Net uplift force per unit length.
$P_{v,total}$	Total uplift force per unit length.
q	Vertical distributed force on the pipeline.
q_u	Collapse load of an anchor.
r	Outer radius of the pipeline.
r_m	Mean radius = (D-t)/2 .
s_u	Undrained shear strength of soil.
s_{um}	Shear strength of soil at mud-line.
s_{u0}	Original shear strength prior to any rate effect or softening.
$s_{u,eff}$	Effective undrained shear strength of soil at considered depth.

$s_{u,ref}$	Undrained shear strength at the soil surface.
S_t	Sensitivity of clay.
t	Pipe wall thickness.
t_{con}	Time of consolidation.
t_{plough}	Depth of ploughing.
T_i	Initial temperature of pipeline.
T_{if}	Temperature of transporting product.
T_s	Ambient temperature.
ΔT	Temperature difference between transporting fluid and the outside of pipe.
Δu	Displacement rate.
u	Displacement of pipeline.
U	Average degree of consolidation.
V_H	Horizontal resistance on pipeline.
$V_{H,res}$	Residual horizontal resistance on pipeline.
$V_{H,berm}$	Berm resistance during large pipe displacement.
$V_{H,max}$	Maximum horizontal resistance on pipeline.
V_p	Penetration resistance on pipeline.
V_t	Total ultimate uplift force of the pipeline.
V_u	Uplift resistance on pipeline.
$V_{u,max}$	Vertical bearing capacity on pipeline.
H	Pipe embedment depth (distance between the top surface of sea-bed and the top of the pipeline).
w_d	Reverse embedment depth or depth of the pipe bottom from the top of the soil-bed.
w_h	Depth from sea-bed to the bottom of the anchor;
W_P	Pipe weight per unit length.

W_s	Total weight of the soil block above the pipe per unit length.
W_s'	Effective (buoyant) weight of the soil block above the pipe per unit length.
W_p'	Effective (buoyant) weight of the pipe per unit length.
V_a	Axial resistance of pipes.
$V_{a,max}$	Maximum axial resistance of pipes.
Δz	Thickness of soil layer.
Z	Considered depth within the seabed.
Z_w	Water depth.
α	Thermal expansion coefficient of Steel.
α_a	Activation factor for the clay strength which is between zero and unity.
α_d	Dirac's function determined by elastic or plastic state.
β_1 and β_2	Skew parameters.
β_3	Curve fitting parameter.
γ_p	Unit weight of steel.
γ_{ref}	Reference shear strain rate.
γ_s	Effective unit weight of soil.
γ_s'	Submerged unit weight of soil.
δ	Function of normalised berm area (A_{berm}/D^2) and berm resistance, ($V_{H,berm}$).
δ_a	Axial displacement of pipeline.
$\delta_{a,max}$	Axial displacement corresponding to $V_{a,max.}$
$\delta_{u,max}$	Displacement corresponding to $V_{u,max.}$
δ_u	Vertical displacement.

δ_H	Horizontal displacement.
$\delta_{H,max}$	Horizontal displacement corresponding to $V_{H,max}$.
ε_B	Bending strain of pipeline.
ε_T	Tangent modulus.
ε_S	Secant modulus.
ε_{u}	Total strain at ultimate strength of steel.
ξ_{95}	Accumulated plastic strain at which 95% soil strength reduction occurs by remoulding
θ	Friction angle for the pipeline-cover interface
κ	Slope of recompression curve.
λ	Compressibility of soil.
λ_1 and λ_2	Curve fitting parameter
λ_3	Normalized dent length in the pipe hoop direction
μ	Coefficient of friction between the soil and the model pipe
μ_{ir}	Interface roughness
μ_{it}	Interface tensile capacity
μ_L	Lateral friction coefficients
v_p	Poisson's ratio of steel
v_{ph}	Horizontal pipeline penetration rate
v_{pv}	Vertical pipeline penetration rate
v_s	Poisson's ratio of soil
ρ_c	Density of the outer concrete coating of pipeline
ρ_{if}	Density of transporting material through the pipeline

ρ_i	Density of the transporting
ρ_p'	Submerged Density of steel
ρ_s'	Submerged Density of soil
ρ_w	Density of seawater
σ_o	API yield stress (0.5% strain offset)
σ_u	Specified minimum tensile strength of steel
σ_v'	Effective stress in the backfill
σ_y	Specified minimum yield strength of steel
τ_{int}	Pipe/soil interface shear strength
$\tau_{u,ave}$	Average drained shear strength
ϕ	Friction angle of soil
ψ	Dilation angle of soil

LIST OF ABBREVIATIONS

ALA	American Lifeline Alliance
API	American Petroleum Institute
CMOS	Complementary Metal-Oxide Semiconductor
DNV	Det Norske Veritas
DSLR	Digital Single-Lens Reflex
FE	Finite Element
FP	Fin-integrated Pipe section
FT	Full Tension condition
HP-HT	High pressure-high temperature
IS	Indian Standard code
LVDT	Linear Variable Differential Transducer
MC	Mohr Coulomb model
MCC	Modified Cam Clay model
MPT	Miniature Pressure Transducers
NT	No Tension condition
ROI	Region Of Interest
RP	Regular Pipe section
scm	standard cubic meters